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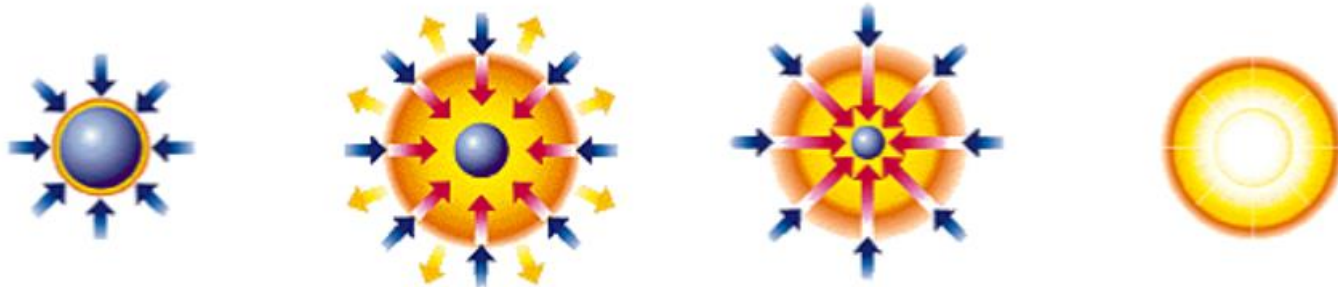
A Novel High Frequency, High Bandwidth, Three Phase Mach Zehnder Optical Data Link

Logan Norman, Hermann Geppert-Kleinrath, Yongho Kim, Kevin Meaney

12/16/2021

Inertial Confinement Fusion (ICF)

1. Incident lasers heat up a DT fuel filled capsule
2. The outer high density carbon layer burns off
3. Rapid compression of inner layers
4. Fusion of DT fuel



1) Atmosphere formation: Laser beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

2) Compression: Fuel is compressed by the rocket-like blowoff of the hot surface material.

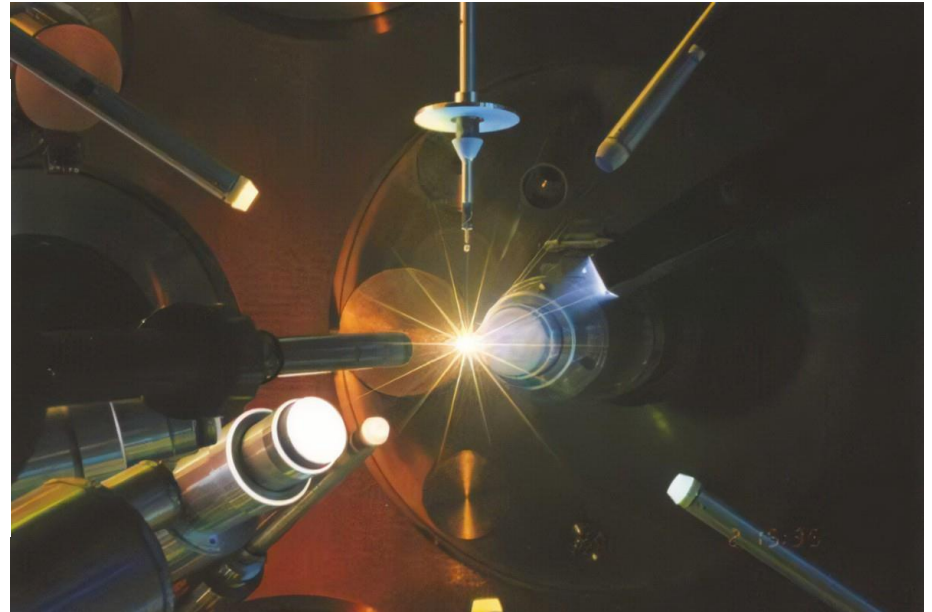
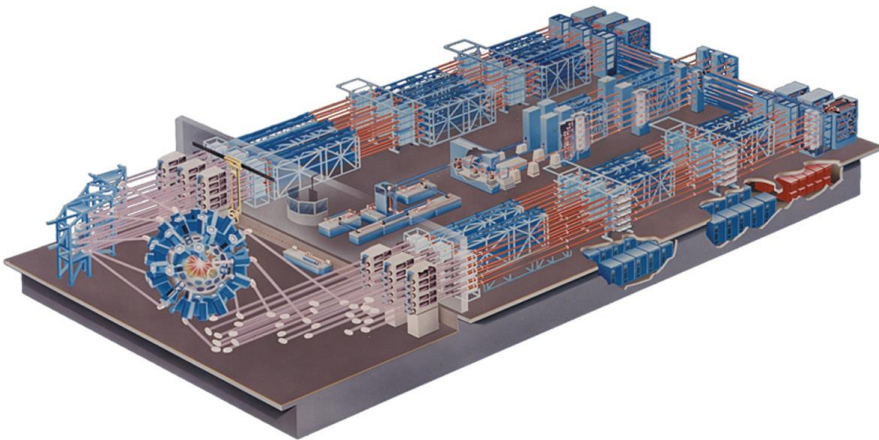
3) Ignition: During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 degrees Celsius.

4) Burn: Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

→ Laser energy → Blowoff → Inward transported thermal energy

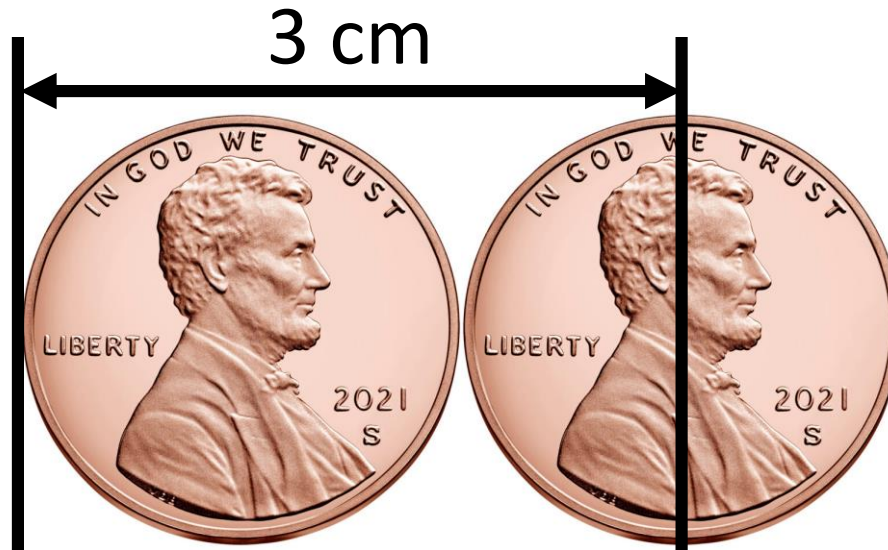
Inertial Confinement Fusion (ICF)

- Several places have constructed large test chambers for experimenting with Inertial Confinement Fusion, including the National Ignition Facility (LLNL) and OMEGA (LLE)
- Each facility has many diagnostic measurement devices being used to evaluate different aspects of the experiment (e.g. Neutron yield, temperature, density, reaction rate, etc.)



High Bandwidth Signals

- The fusion reactions that take place at the facilities mentioned happen at a very fast rate and dissipate quickly with very high yields of gammas/neutrons
- The resulting signal from the PMT has a FWHM on the order of 100 picoseconds, which is the time it takes light to travel 3 centimeters



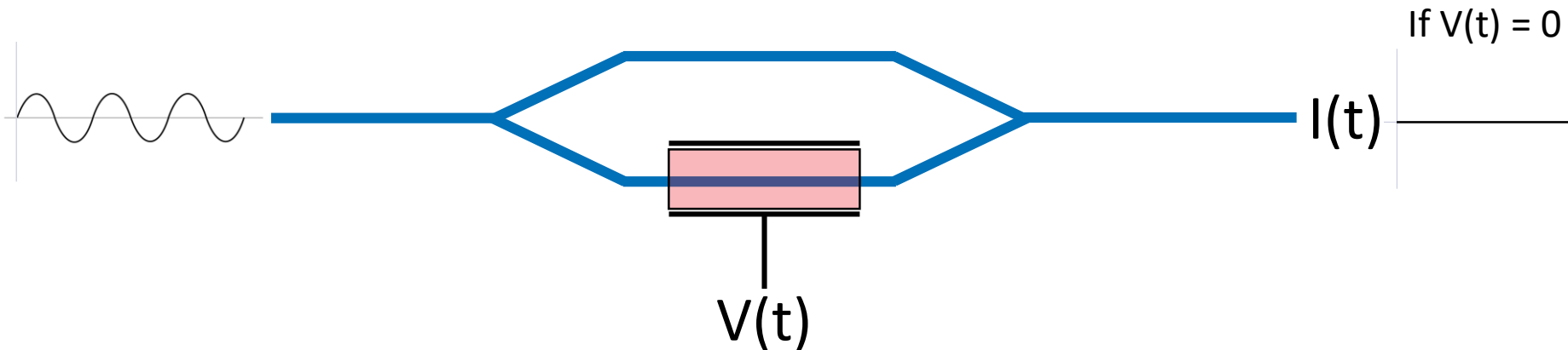
Data Transfer Issues

- A “shot” is an event where a single fuel capsule is imploded
- Radiation and the EMP from laser pulse forces data collection equipment to a distanced shielded room to prevent damage
- Thus the signal must travel approximately 150 Feet
- Higher frequency signals and longer cable length degrades the signal rapidly
- The solution was to convert the electrical signal to an optical signal for transmitting over the large distance

Mach Zehnder Modulator Solution

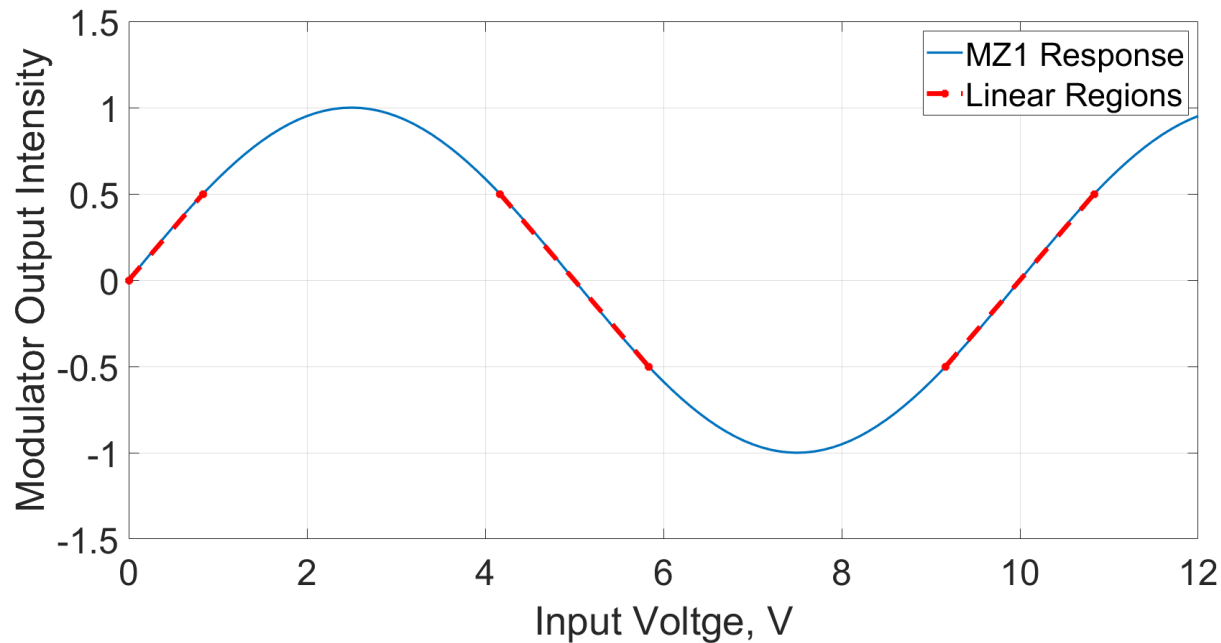
- A Mach Zehnder Modulator has an optical signal constantly passed through a piezoelectric crystal to introduce a phase shift
- An electric field induced by an input voltage causes this crystal to stretch, and in turn modulates the optical signal
- This modulation can be measured and then an input voltage signal can be reconstructed

$$I(t) = A + B \sin \left(\frac{\pi}{V_{\pi}} V(t) + \varphi \right)$$



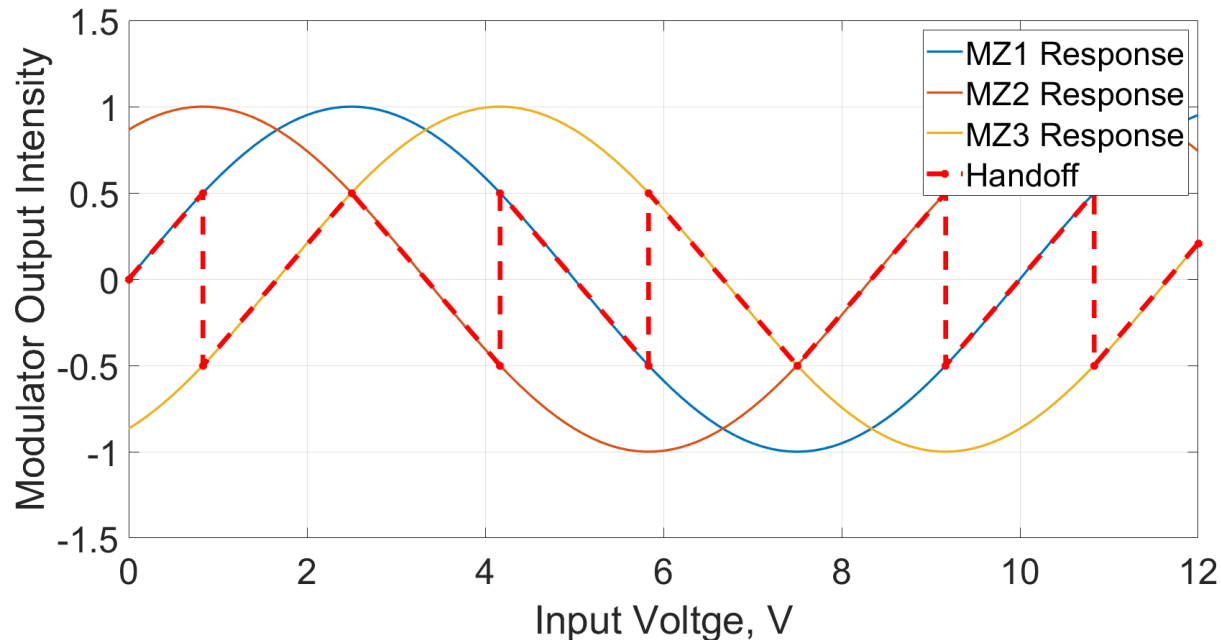
Dynamic Range Issue

- The Mach Zehnder Modulators do have limitations
- The dynamic range of an MZ modulator is limited to certain “linear regions” of the MZ response, as shown below
- Outside of these regions the signal is effectively lost due to insensitivity



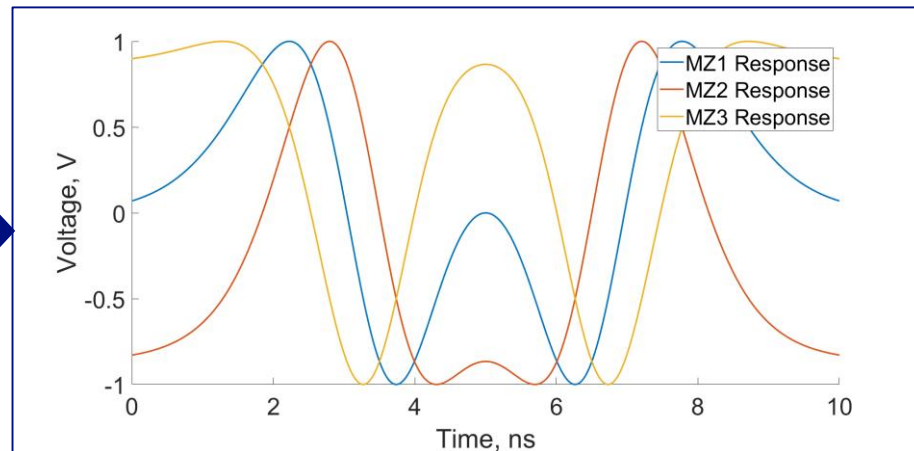
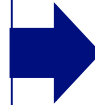
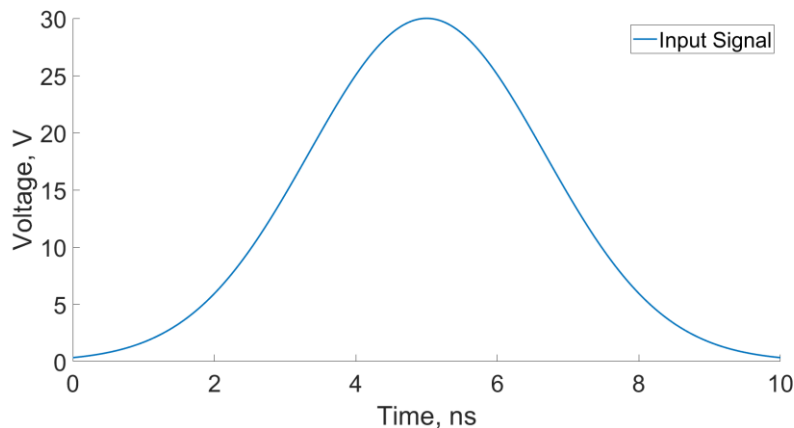
3-Phase Mach Zehnder Solution

- The goal of the 3-Phase Mach Zehnder idea is to remove the dynamic range limitation of the Mach Zehnder
- We would use only the linear region of a single modulator and “hand off” the signal between the other modulators which and stitch together a signal



Reconstruction Program – Initial MZ Output

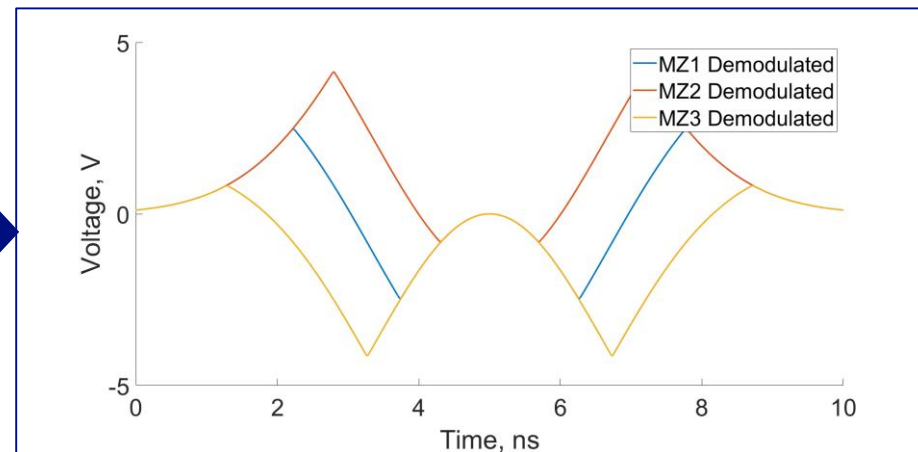
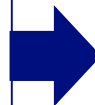
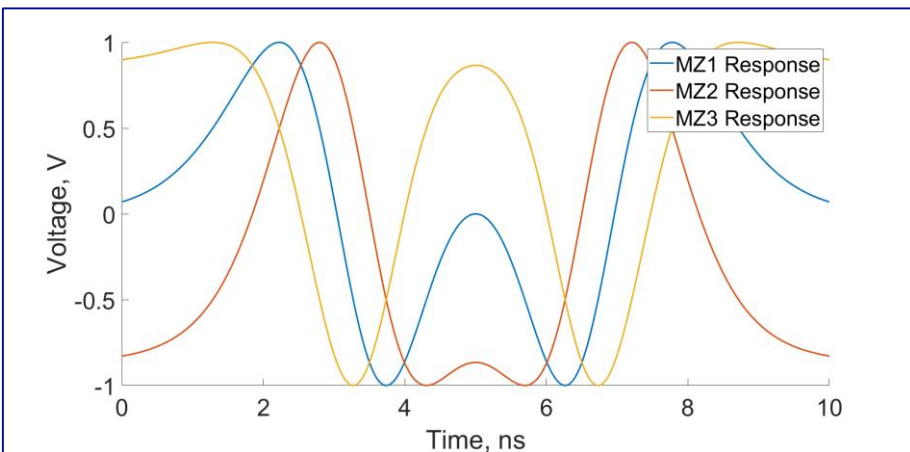
- The reconstruction program has three steps
 - Demodulation
 - Unfolding
 - Stitching
- We can run through an example using simulated data based on a Gaussian input



Reconstruction Program - Demodulation

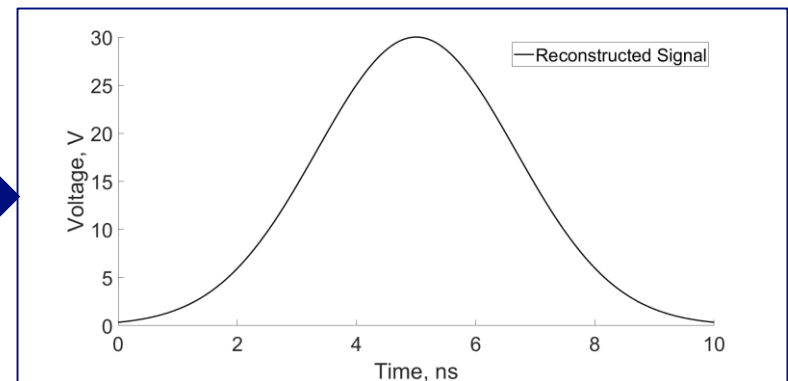
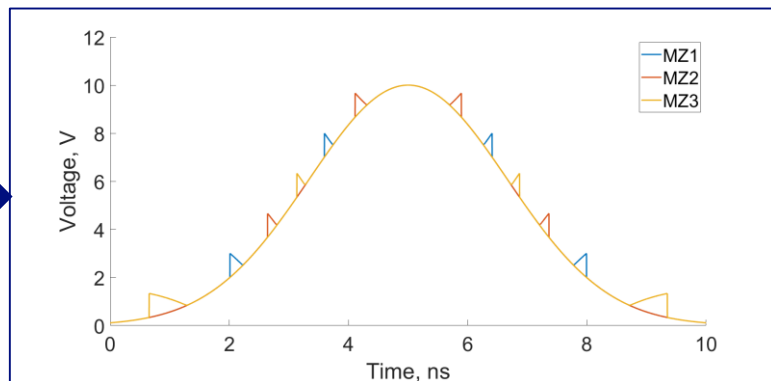
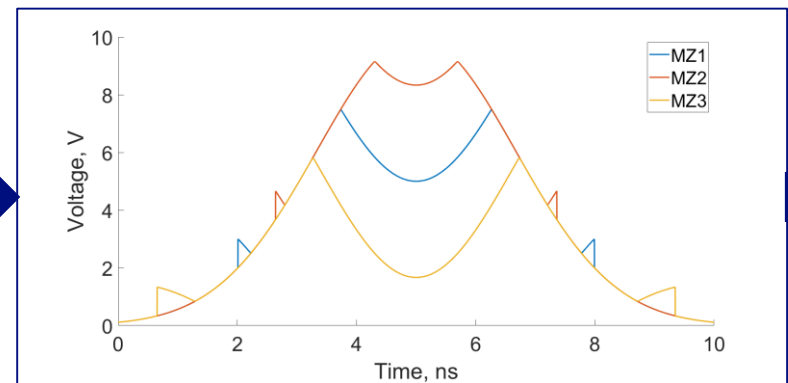
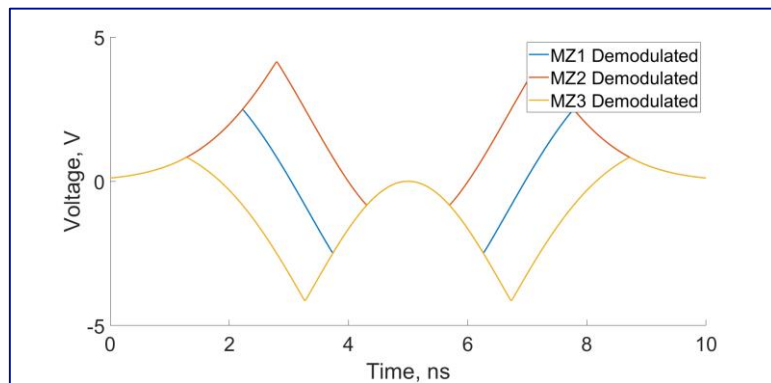
- The reconstruction program has three steps, the first of which is demodulation
- This is simply plugging the intensity output of the MZ into the inverse of the modulation equation

$$V(t) = \frac{V\pi}{\pi} \left[\sin^{-1} \left(\frac{1}{B} I(t) - A \right) - \varphi \right]$$



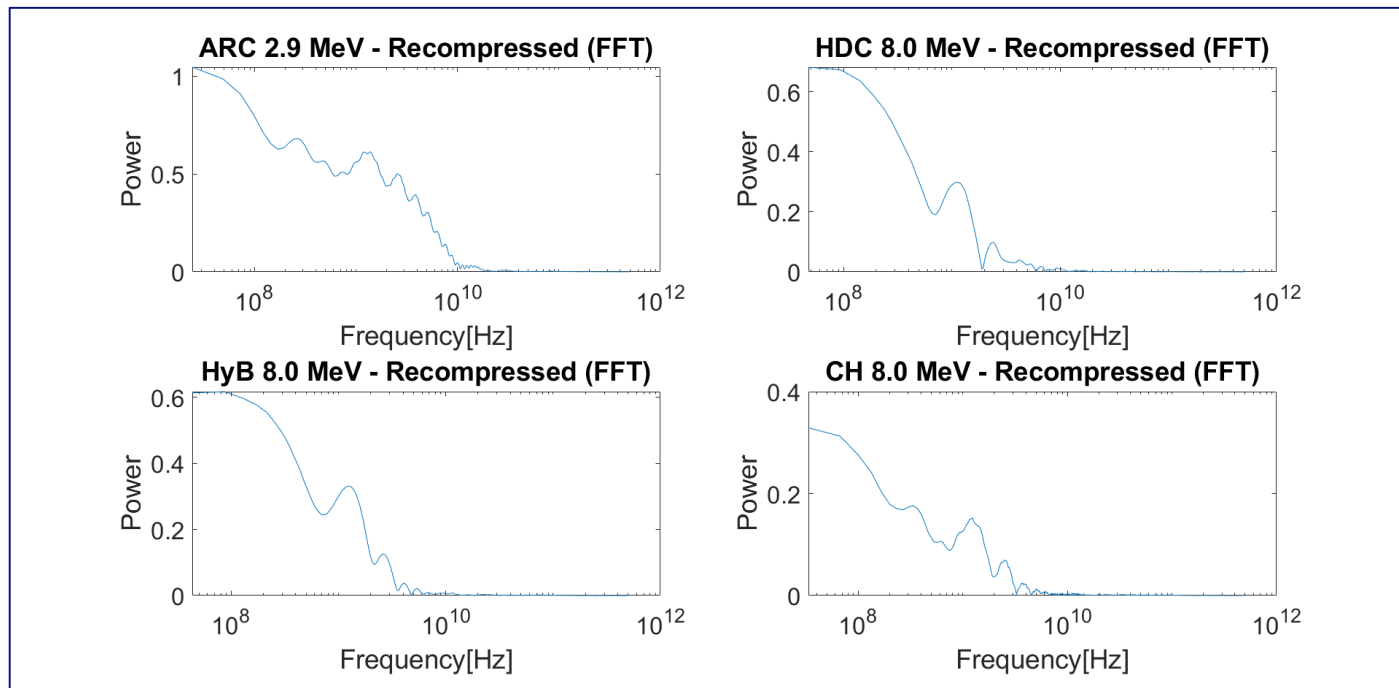
Reconstruction Program – Unfolding & Stitching

- You must then “unfold” the signal, by way of flipping the signal in between peaks around increments of V_{pi} in several steps
- Stitching refers to constructing a signal by selecting portions from each Mach Zehnder that are not in a “rollover” state and stitching them together



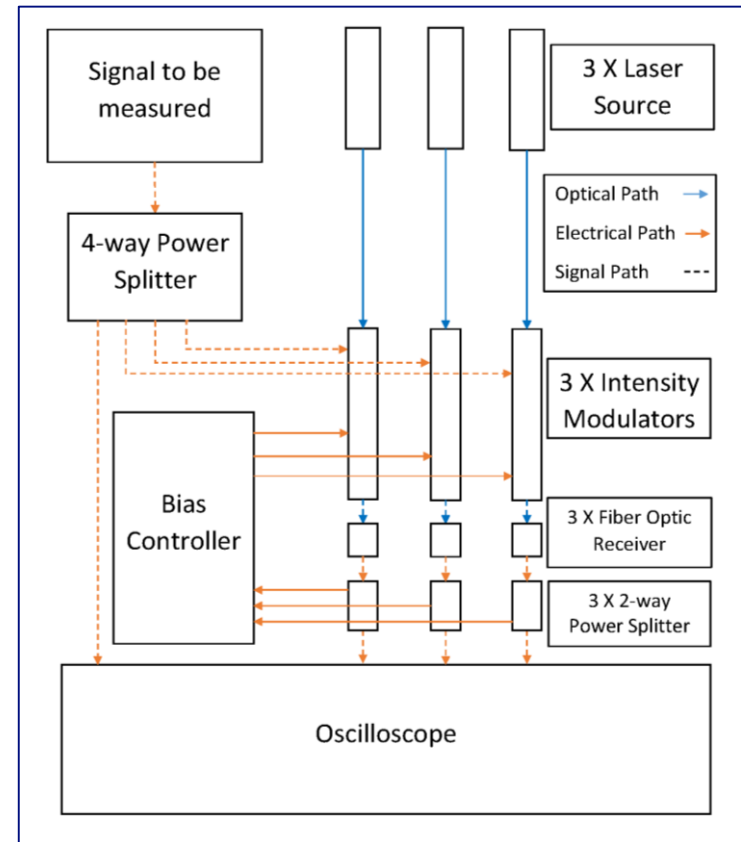
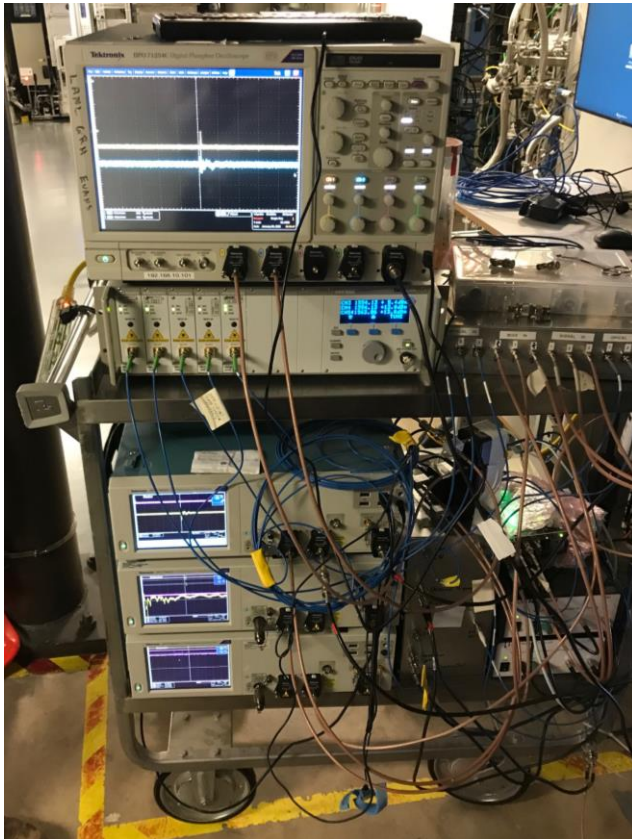
Bandwidth Needs

- We performed a Fast Fourier Transform on previous NIF data to get an estimate of the exact bandwidth needs
- 10 GHz is the upper range
- Our equipment is rated at 12.5 GHz or higher



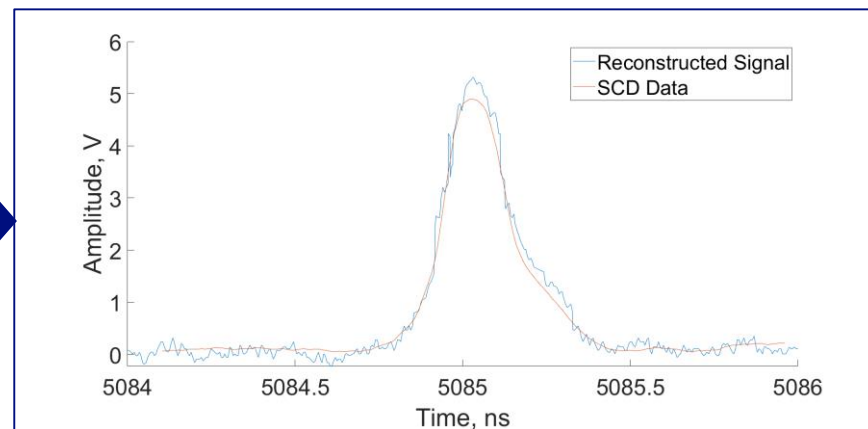
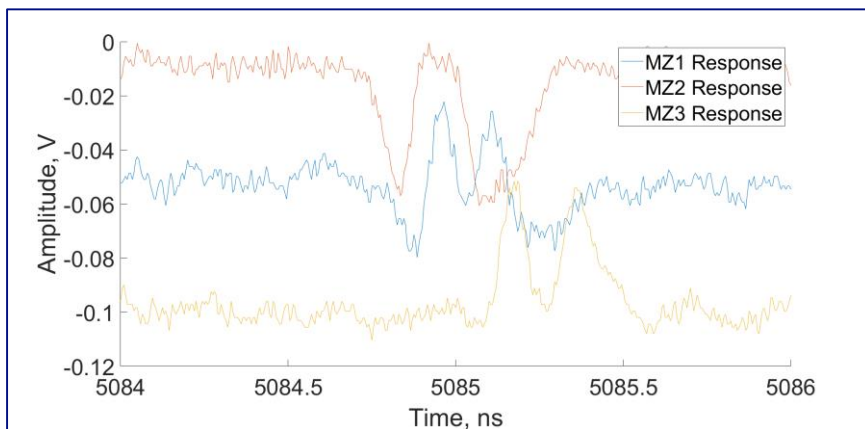
Physical Setup

- We designed and constructed a physical setup using the bandwidth needs as a guideline for component selection, and we tested it at OMEGA

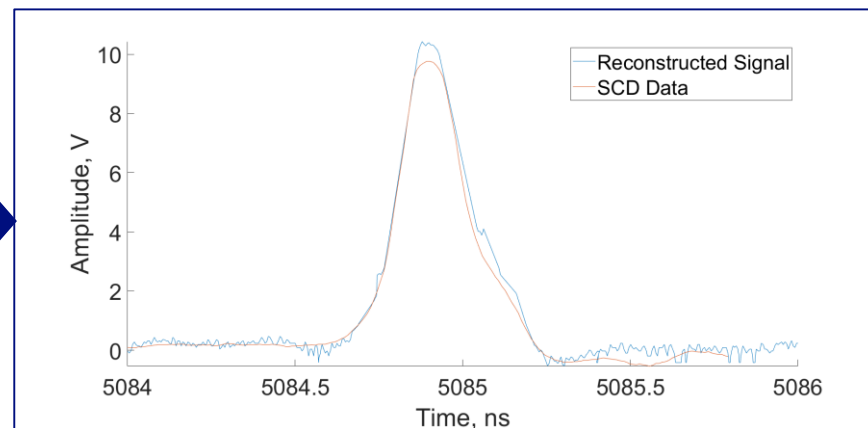
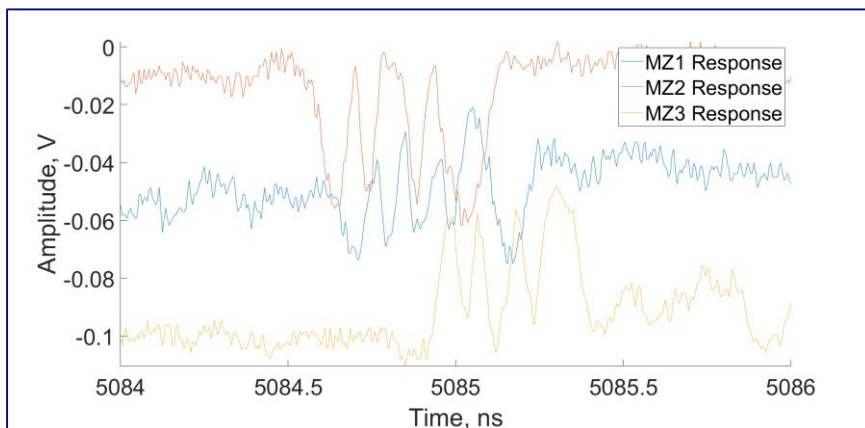


OMEGA Results

SHOT 12: 200 GS/s w/ Attenuation



SHOT 10: 200 GS/s w/o Attenuation



Summary

- ICF produces high yield, high bandwidth signals that must be sent over large distances
- A three phase Mach Zehnder modulator system helps resolve many of the issues faced with measuring these signals
- This setup requires a three step reconstruction program
- The testing results from OMEGA show this setup was successful and is ready for fielding at NIF